Evaluating airborne and ground based gamma spectrometry methods for detecting particulate radioactivity in the environment: a case study of Irish Sea beaches.

A.J. Cresswell, D.C.W. Sanderson

Scottish Universities Environmental Research Centre

Scottish Enterprise Technology Park

East Kilbride

G75 0QF

UK

Abstract

In several places, programmes are in place to locate and recover radioactive particles that have the potential to cause detrimental health effects in any members of the public who may encounter them. A model has been developed to evaluate the use of mobile gamma spectrometry systems within such programmes, with particular emphasis on large volume (16 litre) NaI(Tl) detectors mounted in low flying helicopters. This model uses a validated Monte Carlo code with assessment of local geochemistry and natural and anthropogenic background radiation concentrations and distributions. The results of the model, applied to the example of particles recovered from beaches in the vicinity of Sellafield, clearly show the ability of rapid airborne surveys conducted at 75 m ground clearance and 120 kph speeds to demonstrate the absence of sources greater than 5 MBq ^{137}Cs within large areas (10-20 km^2 h^{-1}), and identify areas requiring further ground based investigation. Lowering ground clearance for airborne surveys to 15 m whilst maintaining speeds covering 1-2 km^2 h^{-1} can detect buried ^{137}Cs sources of 0.5 MBq or greater activity. A survey design to detect 100 kBq ^{137}Cs sources at 10 cm depth has also been defined, requiring surveys at <15 m ground clearance and <2 m s^{-1}

ground speed. The response of airborne systems to the Sellafield particles recovered to date has also been simulated, and the proportion of the existing radiocaesium background in the vicinity of the nuclear site has been established. Finally the rates of area coverage and sensitivities of both airborne and ground based approaches are compared, demonstrating the ability of airborne systems to increase the rate of particle recovery in a cost effective manner. The potential for equipment and methodological developments to improve performance are discussed.

Keywords:

Radioactive particles; airborne radiometrics; Sellafield; Monte Carlo; modelling

1. Introduction

Radioactive particles dispersed into the environment from a variety of sources and mechanisms have resulted in contamination of locations throughout the world, in several cases with actual or potential radiological significance. The sources and characteristics of particles from weapons testing and accidents, nuclear powered satellite re-entry, use of depleted uranium munitions, dumped radioactive objects, nuclear fuel reprocessing and routine and accidental releases from nuclear power plants have been reviewed elsewhere (IAEA 2011). It has been noted that the accident at Fukushima in 2011 is also expected to have released radioactive particles into the environment (Salbu 2011). Industrial or medical radiography sources have been lost or stolen, and, following scrap metal processing, have been broken up into a larger numbers of widely distributed sources resulting in the worst cases in hundreds of members of the public receiving significant, and in some cases lethal, radiation doses (Nénot 2009, IAEA 1988, 2002). There is also a potential for the malicious dispersion of radioactive materials, which it is expected could result in inhomogenous contamination by radioactive particles (Harper *et.al.* 2007). Finds of radium contaminated objects, from luminous aircraft instrumentation buried at a local military site, have also been made at Dalgety Bay in Scotland since 1990 (Dale 2011, Black *et.al.* 1994), and other radium rich particles have been recovered from many former industrial areas. Risk assessments combining habit surveys and particle distribution information can be used to estimate the potential risk to members of the public. Where necessary measures to reduce the potential harm to members of the public can be taken, including restricting access or remediation of contaminated sites.

In Cumbria and Caithness, programmes of long term intensive monitoring and particle recovery have been implemented, with the aim of reducing public risks due to encountering such particles. Using ground based, mainly vehicular, systems surveys of the beaches around Sellafield and Dounreay have been conducted to locate and recover radioactive particles discharged into the sea from these sites and washed ashore. Over 1500 radioactive particles (Sellafield 2011, Tyler *et.al.* 2010, Toole 2007) have been recovered to date. The ground based survey approach allows detailed surveys of small areas with the ability to locate radioactive particles with very low activity. It can also be coupled to direct recovery operations when particles or contaminated sources are located. However, it is a very time intensive and expensive approach, especially where radioactive particles may be present over large areas, with area coverage rates typically ~1.5 ha h^{-1}. In the coastal environment only limited areas can be surveyed within single tidal cycles; thus introducing the potential for reworking of the beach sediments to take place before an individual survey is complete. Vehicular access to entire shorelines, especially rocky sections, is also limited.

Experience from airborne surveys shows that such approaches are capable of covering much larger areas in a cost effective manner, without hindrance from surface conditions, than vehicular approaches. Airborne survey equipment was deployed to locate fragments from the Cosmos-954 satellite (Bristow 1978, Grasty 1980), with more than 4000 sub-millimetre sized particles upto several MBq activity recovered. An airborne survey was conducted over the urban area of Goiânia in Brazil, following the dispersion of ^{137}Cs in the form of CsCl salt when a hospital radiotherapy unit was dismantled, to locate sources and direct recovery operations (IAEA 1988). Airborne surveys have also been used to search for sources lost in an explosion at an oil terminal (Sanderson *et.al.* 1988), and stolen from an oil exploration site (Sanderson & Allyson 1991). Airborne survey approaches can be used to locate zones within large areas where ground based confirmation and recovery operations would be most effectively directed, or to demonstrate the absence of the most hazardous radioactive particles above detection limits. Used together with appropriate ground based support this could increase the effectiveness, efficiency and levels of public protection of programmed work targeting areas contaminated with radioactive particles.

The work reported here uses a radiation transport and detector response model to evaluate area coverage rates and detection limits for a range of survey designs, and to design surveys to meet specified detection requirements. The model is applied to the detection of Sellafield derived particles on beaches in Cumbria, using appropriate local geochemistry and background radiation distributions (Sanderson & Cresswell 2010, Cresswell & Sanderson 2011). The detection limits and rates predicted for airborne surveys are compared with ground based approaches, including those currently used in beach monitoring.

2. Background

In July 2003, a particle was recovered from the beach near Sellafield following routine strandline monitoring using hand-held Geiger-Müller detectors (Hemming 2008). Subsequent analysis showed the particle contained 24 kBq ^{90}Sr. A programme of beach monitoring and recovery was initiated in November 2006. By 31st March 2011 1233 radioactive particles had been removed from beaches between Allonby and Drigg Point (Sellafield 2011). The majority had activities below 100 kBq, and consisted of mostly ^{137}Cs, ^{241}Am and some ^{60}Co. The most active of the finds recovered, in the range of 100-1000 kBq, have all been from the Sellafield foreshore.

A number of particles were discovered in the offshore environment of Dounreay in 1997, prompting the commencement of a beach survey programme that has recovered over 350 particles with several having activities in excess of 100 kBq (Tyler *et.al.* 2010, Toole 2007).

An advisory group established by the regulators at Dounreay developed a classification for particles; >1 MBq “significant”, 100-1000 kBq “relevant” and <100 kBq “minor” (DPAG 2008).

Current survey practice at both locations utilises the Nuvia Groundhog system, which in the most recent version (Synergy) consists of 5 high volume (96x96x400 mm) NaI(Tl) detectors providing contiguous lateral cover of 2 m and 8 FIDLER (Field Instrument for the Detection of Low-Energy Radiation) detectors, at a height of 200 mm above the beach surface mounted on a Hillcat all terrain vehicle (Davies *et.al.* 2007, Dennis *et.al.* 2007, Tyler *et.al.* 2010). The particle detection algorithm uses a three window approach, with spectral windows around the energy of the radionuclide of interest (eg: 662 keV for ^{137}Cs) and spectral windows above and below this, with a rolling average background. The use of more information from the spectrometer was considered too computationally intensive (Davies *et.al.* 2007). A hand held version of the same system with a single detector crystal is also used for beach surveys. A vehicular system utilising four Fidler probes designed to optimise detection of ^{241}Am has been used in monitoring the Maralinga weapons testing site (Long *et.al.* 2004).

Airborne Gamma Spectrometry (AGS) is an established technique for rapidly measuring the distribution of radionuclides in the environment (IAEA 1991, 2003, Sanderson *et.al.* 1994a,b). It is well suited to both wide area surveys and detailed surveys of smaller areas, especially where the speed of the method is important in recording dynamic environments or where access from the ground is impracticable or potentially hazardous. The method can easily map the distribution of activity on foreshores within a single tidal cycle, including both beach areas easily accessible to ground based monitoring and boulder fields where access is more restricted. A survey of the entire Cumbrian coast from Gretna to Duddon, over three low tide cycles with a total of 3h survey time, was conducted in March 2000 (Sanderson *et.al.* 2000). During this survey an anomalous ^{137}Cs signal was observed to the south of St Bees on a gravel beach, which would not normally be expected to retain activity. A short, 15 minute, follow-up flight was conducted at lower speed and altitude to examine this further showing several small area features producing count rates consistent with ~10 MBq point sources. This experience has demonstrated an ability to locate small scale features with total activity ~10 MBq ^{137}Cs using airborne methods. The observed features were reported to the Environment Agency during the survey in March 2000, but were not investigated further at the time. Additional analysis and visualisation of this data was conducted in 2009, with a ground based survey using a portable gamma spectrometry system with a 3x3" NaI(Tl) detector conducted in June 2010 (Cresswell *et.al.* 2010). Figure 1 shows the ^{137}Cs distribution observed from the March 2000 airborne survey, with the corresponding distribution from the June 2010 survey. The 2010 survey confirmed the presence of the activity observed in 2000, showing it to be from dispersed patches rather than point sources.

3. Method

The specific example of the particles on the beaches of Cumbria has been investigated using Monte Carlo simulations, with the code verified, and using appropriate mass attenuation coefficients for the local geochemistry. The natural and anthropogenic backgrounds have been examined, and simulations conducted for a selection of typical backgrounds. The response of airborne and ground based detectors to point sources on the surface and at 10 cm depth has then been simulated, and analysed to determine detection limits under different scenarios.

3.1 Simulation Code

A Monte Carlo code specifically developed and validated for airborne survey geometries (Allyson 1994, Allyson & Sanderson 1998, Cresswell *et.al.* 2001) has been used here. This incorporates a statistical approximation approach to significantly increase simulation speeds for the large source to detector geometries typical of airborne systems. Validation of this code demonstrated excellent agreement with published simulations and measurements of stripping matrices, which are highly sensitive to scattered energy components, on calibration pads (Allyson 1994, Allyson & Sanderson 1998). Measurements on a range of field sites (Tyler 1994) and a calibration site developed for the Resume95 International Exercise in Finland (Sanderson *et.al.* 1997) validated this code against field conditions. Simulations of complex fission product sources showed very good agreement with experimental data collected over a 12 month period (Cresswell *et.al.* 2001). Full energy sensitivities determined from the model can also be compared to field measurements. At the Resume95 Exercise in Finland, peak count rates of 1200 ± 60 were recorded over a 2.8 GBq ^{137}Cs source (Sanderson *et.al.* 1997), with a corresponding count rate of 0.43 cps MBq^{-1}, at a survey height of 60m. The Monte Carlo model predicts a count rate of 0.34 cps MBq^{-1}, at 75m height, which is in good agreement with the experimental data. An analytical model considering only the attenuation of primary gamma rays in intervening media, using equation 1, predicts a count rate of 0.32 cps MBq^{-1}.

$$\dot{N} = A\varepsilon \frac{A_D}{4\pi h^2} e^{-(\mu_a h + \mu_s d)}$$

where: A is the source activity, A_D is the detector area, ε is the detector full-energy peak efficiency, h is the detector height, d is the source burial depth, and μ_a and μ_s are the linear attenuation coefficients for air and soil respectively.

The ^{238}U and ^{232}Th series contain 762 and 245 emissions respectively. To simplify the simulation of these series, or similar complex emission schemes, approaches previously used include truncating the emission intensity so that only the most intense emissions are simulated (Allyson 1994, Allyson & Sanderson 1998) and binning the emissions into wide energy ranges (Cresswell *et.al.* 2001). For this work a new approach was used. Lists of all the gamma emissions from each of the ^{238}U series and ^{232}Th series, assuming secular equilibrium, with relative intensities were produced. These were used to simulate the response of the detector to each series using an intensity weighted random sampling of the emission lines. The Monte Carlo code was validated again for a 3x3" NaI(Tl) detector on calibration pads at SUERC and for the 16 litre detector at 75 m over a beach section in West Cumbria. Natural series specific activities determined from airborne measurements during the March 2000 survey (Sanderson *et.al.* 2000), using a spectral windows method with stripping, were used to generate a simulated spectrum for the natural series at a location near St Bees. This simulated spectrum, with the corresponding measured spectrum, is shown in Figure 2. It can be seen that for the natural peaks there is an excellent agreement between the simulated and measured spectra, the measured spectrum includes a ^{137}Cs component that had not been simulated. The residual spectrum produced by subtracting the fitted natural spectrum from the measured spectrum clearly shows the ^{137}Cs peak and the scattered component.

3.2 Characterisation of Cumbrian Beaches

Literature data were used to characterise the geochemistry of the beaches of West Cumbria to determine appropriate values for the radiation attenuation coefficients of material on the beaches. The coastal region of West Cumbria south of St Bees Head has a Triassic-Permian sandstone bedrock, with superficial glacial deposits of material derived from the Lake District divided into three main groups listed in Table 1 (Cooper *et.al.* 1993), with major elemental concentrations from stream sediments (BGS, 1992). The Skiddaw and Borrowdale groups are the most significant source for the glacial deposits in the coastal region around Sellafield.

Gamma ray interaction probabilities are functions of energy and atomic number (Z) of the atoms in the material. The effect of varying geochemistry is largely related to concentrations of elements with contrasting Z, and impact the photoelectric absorption coefficients, thus low interaction energies, most significantly. Hypothetical rock compositions were determined, with major element concentration values consistent with andesitic volcanic rocks (taken from Bryant *et. al.* 2006), similar to those of the Borrowdale Volcanic Group. These compositions are listed in Table 2. The mass attenuation coefficients for each composition were determined from values tabulated by Storm and Israel (1970), and the total mass attenuation coefficients plotted in Figure 3. It can be seen that for energies >200 keV the attenuation coefficient is independent of the elemental composition. At lower energies the composition, especially for Fe content, becomes more significant.

The beach materials between St Bees Head and Sellafield consists of mostly exposed bedrock (Sandstone) and deposits of sand and gravel. The beach materials can be derived from erosion of the bedrock, erosion of the superficial glacial deposits along the shore, alluvial sediments from the river systems and off-shore sediments deposited at the end of the last glaciation. The onshore deposits and alluvial sources would be mixed materials from the Skiddaw and Borrowdale groups. The offshore deposits are largely derived from glacial transportation of material from the Scottish Southern Uplands (Akhurst et.al. 1997).
The trace element geochemistry of local rocks taken from BGS (1992), samples collected during the NIREX geological investigations of the Sellafield siteand samples of sediment

collected from the Solway in 1980 and 1995 (Jones *et.al.* 1999, 2009), considered to be derived from off-shore sources, and a small number of samples collected from the coast and analysed for Fe content (McCubbin *et.al.* 2004) were examined. These are given in Table 1. Given that the Fe content is the most significant factor in the attenuation constants, it was decided to use the composition of St Bees Sandstone to determine the mass attenuation coefficients used in the Monte Carlo code. It is recognised that this will introduce some additional uncertainties in simulations below 100 keV, where the sensitivity of the attenuation coefficients to geochemistry of the matrix is more significant.

Repeating the analysis reported here for other areas would require an assessment of the local geochemistry, but if there is sufficient similarity to West Cumbria then the simulation results produced in this work could be applied for higher energy gamma sources.

3.3 Examination of Natural and Anthropogenic Backgrounds

Natural radiation levels along the West Cumbrian coast line have been determined from airborne surveys conducted in 1990, 1992 and 2000 (Sanderson *et.al.* 1990, 1992, 2000). Working values for calibration factors were used for these surveys, however as noted the specific activities derived for these measurements produce simulated natural series spectra that are consistent with measured spectra. Log-normal histograms were used to determine the 10^{th}, 50^{th} and 90^{th} percentiles for ^{40}K, ^{214}Bi (^{238}U series) and ^{208}Tl (^{232}Th series) activity concentrations, as shown in Figure 4. These were then used to approximate high, medium and low activity concentrations for these nuclides along the West Cumbrian coast given in Table 3. In addition, ^{137}Cs activity concentrations and distributions at finer scales have been estimated from ground based measurements conducted by Nuvia during surveys for radioactive particles, and from ground based measurements conducted by SUERC in 2010

(Cresswell *et.al.* 2010). These show that for several beaches there are low levels of ^{137}Cs activity per unit area observed from the air (Sanderson *et.al.* 2000), however at ground level this activity is observed to be concentrated in discrete patches of 5-20 m dimensions. In some locations these patches start to merge into larger features. Samples recovered from these patches and analysed by SUERC and Sellafield Sites Ltd have consistently produced activity concentrations of ~50 Bq kg^{-1}. For moderately dense patterns of such patches, occupying more than 25% of the area, the spatial extents of the signals approximate uniform distributions. Uniform ^{137}Cs distributions at three different distributions corresponding to complete coverage and area coverages of half and one quarter, were taken to approximate the effect of moderately dense distribution of dispersed ^{137}Cs patches, as listed in Table 3.

Again, to apply the work reported here to other locations would require an assessment of the natural and anthropogenic backgrounds typical of that area.

3.4 Simulations Conducted and Analytical Approach

Simulations were conducted for a standard 16 litre (40x40x10 cm) NaI(Tl) detector pack at 75 m and 15 m heights, and a 3x3” NaI(Tl) detector at 1.2 m. Simulated 1 s spectra were produced for a specific activity of 1 Bq kg^{-1}, assuming uniform distribution laterally and to a depth of 50 cm, for ^{137}Cs, ^{40}K, ^{238}U series and ^{232}Th series. These spectra were used to generate stripping matrices for the detectors. Single patches of uniform 50 Bq kg^{-1} ^{137}Cs specific activity and 10x10 m square dimensions were also simulated. Spectra for 1 s measurements for each background scenario were then produced by scaling these spectra by the specific activities in Table 3 and summing them, with gross count rates for spectral windows corresponding to the natural series activities, and ^{241}Am and ^{137}Cs, calculated.

These were processed using a windows stripping method (IAEA 1991, 2003, Sanderson *et.al.* 1994a, Allyson & Sanderson 1998, Cresswell *et.al.* 2006) to estimate stripped count rates and uncertainties for measurements of 1, 2, 4, 8, 16 and 32 s. These were used as values for the background and uncertainty of the ^{137}Cs and ^{241}Am full energy peaks under ideal circumstances.

Spectra from point sources of ^{241}Am on the surface, and ^{137}Cs on the surface and at 10cm burial depth were also simulated at a range of lateral offsets. These were scaled to different source activities, and added into the background spectrum appropriate for each scenario. The gross count rate and uncertainty for the ^{137}Cs or ^{241}Am windows was determined, and the previously determined background count rate subtracted. A significance measure, defined as the ratio of the net count rate to its uncertainty, was determined – initially for individual short spectral accumulation times (1 s), and then integrated to represent the practical timescales for evaluation of airborne or ground based data sets.

Two airborne survey conditions were studied; a “rapid survey” corresponding to the surveys of the whole Cumbrian coastline in March 2000, and a “low and slow survey” corresponding to the detailed examination of unexpected ^{137}Cs features south of St Bees (Sanderson *et.al.* 2000). For the backpack a survey was simulated approximating the June 2010 survey. The survey parameters and area coverages are summarised in Table 4.

The extent to which the recovered particles might have contributed to observed signals in earlier AGS surveys has also been examined. The data for the activity, location and depth for all the finds recovered until the end of 2010 were examined to determine the depth distribution of the finds. This allowed an assessment of additional source simulations needed to approximate to the actual depths of finds recovered, as shown in Figure 5. Almost 70% of the recovered particles were found in the top 5 cm of the beach, with approximately 20% found between 5 and 10 cm depth. Very few particles have been recovered from below 20 cm depth. Additional source simulations at 5 cm, 15 cm and 20 cm were conducted to supplement the 0 cm and 10 cm simulations, at 15 m and 75 m ground clearance and used to simulate the response of the airborne detectors used in earlier surveys to the particles that had been recovered. For the existing survey data, the natural series specific activities determined were used to produce simulated natural spectra assuming 75 m ground clearance. Each measurement was divided into 500 ms sections assuming constant velocity during the measurement, with the midpoint for each section determined. The contribution from any source within 220 m was then determined for each measurement section and the total ^{137}Cs spectrum for the entire measurement produced. This was added back into the simulated natural spectrum to determine if a measurable signal was produced. In addition, the simulated natural spectra were subtracted from the measured spectra and the residual spectrum used to estimate the ^{137}Cs contribution to each measurement.

4. Results

The significance ratio was plotted for static measurements over the source of different integration times, and for 1s measurements along a transect over the source and offset by half the line spacing. For example, plots of significance for transects over ^{137}Cs sources for the medium natural activity scenario are shown in Figure 6. Similar plots are obtained for transects over sources with different uniform backgrounds. For individual measurements of 1s duration, detection limits based on significance being greater than 2 will be relatively high. For superficial ^{137}Cs a direct overflight should detect a source of ~20 MBq at 75 m and ~700 kBq at 15 m under such survey parameters, and a backpack survey detect ~150 kBq sources.

It is evident that the width of the transect over the buried source is narrower than that over a superficial source, as expected due to the collimating effect of the sand.

In practice, however, it is unlikely that source detection will be based on individual measurements of 1s duration. Longer integration times improve peak to background ratios, with subsequent increases in the significance of individual measurements. By summing spectra around the centre of each distribution on the transects of the form shown in figure 6, an optimal measurement time was estimated. This corresponds to the time to cross 90% of the signal. For the rapid survey this is approximately 8 s, for the low and slow survey 10 s and for the backpack survey 12 s. Longer measurement times were simulated by summing the 1 s spectra around the central peak, with 9 s integration used for both airborne survey parameters and 13 s for the backpack.

Table 4 lists the detection limits (for the integration times specified above) where significance is greater than 2.0, for the three natural background scenarios and three uniform ^{137}Cs distributions added to the medium natural background for the airborne and backpack survey designs. For the rapid survey design, detection limits for ^{137}Cs are in the 5-10 MBq range for superficial sources. This is consistent with the previous observations of features consistent with 10 MBq sources. For the “low and slow” survey design, detection limits would be in the range of 200-300 kBq for superficial ^{137}Cs sources. The backpack survey detection limits for superficial sources are estimated at 30-50 kBq. Detection limits increase by a factor of 4 for sources at 10 cm depth as a result of increased attenuation and collimation of the radiation. Superficial ^{241}Am sources of greater than 1-2 MBq should also be detected in a “low and slow” survey. Reducing ground clearance increases full energy peak count rates by an order of magnitude at 5 m compared to 15 m, thus the significance of full energy peak counts from sources would be much higher at reduced heights. It is estimated that, to achieve a detection limit of 100 kBq ^{137}Cs at 10 cm depth it would be necessary to reduce ground speed to below 2 m s^{-1} and ground clearance to 5-10 m.

The introduction of a uniform anthropogenic background has a minimal effect on detection limits for point sources, assuming that a predictable background count rate can be determined and subtracted, for example using a rolling average background (Cresswell & Sanderson 2009). However, in practice anthropogenic backgrounds are generally less uniform than natural backgrounds. The beaches of Cumbria often contain low levels of dispersed ^{137}Cs activity in small patches of a few metres dimension. The response of airborne detectors to patches of activity have been modelled. Figure 7 shows transects across a 10x10m patch of dispersed ^{137}Cs activity, and across point sources of comparable total activity. It can be seen that the width of the signal from the dispersed activity is marginally wider, but the shapes of the two transects would be indistinguishable within measurement uncertainties at either ground clearance. At ground level the smaller field of view of detectors would assist in the discrimination between dispersed activity patches and point sources, although similar ambiguity would exist for smaller patches of activity. Patches of activity less than the 3x3" detector field of view (ie: 0.5x0.5 m) would contain 5-10 kBq ^{137}Cs activity and would thus be at the limit of detection for such a ground based system using extended integration times. For 1s measurements, needed to produce a transect profile, this activity is significantly below detection limits. The full energy peak count rate data would not be able to identify a point source from a patch of dispersed activity of dimensions significantly smaller than the detector field of view. There may be differences in the scattered components of the spectra which could be utilised to aid identification of point sources, although this has not yet been explored. Detector collimation to reduce the field of view may also help.

For the 75 m simulated data set, all of the particles recovered from the beaches are below the detection limits of the system. And, even the cumulative signal from all the sources would not generate a signal in the detector. The average residual spectra, after subtracting the simulated natural components from the spectra recorded in March 2000, for the beaches at St Bees, Seascale and Drigg, clearly showing the 662 keV peak from ^{137}Cs, are shown in Figure 8. Clearly, these beach environments contain ^{137}Cs activity, but the particles recovered to date do not contribute significantly to the observed spectra.

The March 2000 survey data have also been regridded to allow inventory analysis for the beaches along the Cumbrian coasts, following the procedure developed in that work (Sanderson *et.al.* 2001, 2007). Table 5 lists the total ^{137}Cs activity determined from the airborne survey data for the beaches at St Bees, Seascale and Drigg, along with the total activity for the particles recovered from those beaches. It can be seen that the particles recovered constitute a very tiny fraction of the total ^{137}Cs activity on these beaches (less than 0.001%). For St Bees and Seascale, the Nuvia surveys have covered almost 50% of the beach area, the coverage for Drigg is significantly lower than this. Thus, it can be assumed that the total activity for recoverable particles on these beaches will be higher than that given in Table 5.

5. Discussion

Detection limits for point sources on beaches in Cumbria have been determined by Monte Carlo simulation of the response of mobile gamma spectrometry systems, coupled to a detailed review of the existing natural and anthropogenic sources in the target environments. The Monte Carlo code used was developed specifically for rapid and accurate simulation of airborne detector geometries, and simulates the full emission spectra of natural activity series. It has been validated for 3x3" NaI(Tl) detectors on calibration pads, and for the 16 litre NaI(Tl) airborne survey detector pack using data collected over beaches in Cumbria in March 2000.

Two survey designs previously used in airborne measurements of Cumbrian beaches have been simulated. A rapid airborne survey specification would identify any areas with patchy ^{137}Cs activity distributions where more detailed airborne and ground based follow up would be required, but would be insensitive to any of the sources so far recovered from the beaches around Sellafield. At least 20 of the particles recovered from the Dounreay foreshore would be detected by an airborne survey under such conditions. A low and slow airborne survey would be capable of detecting sources of 200-1000 kBq ^{137}Cs depending on burial depth, in conditions of approximately uniform background radiation. Of the particles recovered from the beaches in Cumbria up to December 2010, 9 have had ^{137}Cs activities in excess of 200 kBq of which one (308 kBq recovered in October 2009 from a depth of 7 cm on the Sellafield foreshore) is close to the detection limits determined for a 'low and slow' airborne survey with the other particles including all 5 with activities in excess of 500 kBq recovered from depths in excess of 10 cm. In Caithness, ~50 particles have been recovered with ^{137}Cs activities in excess of 500 kBq up to March 2011, with the majority of these from the Dounreay foreshore and at relatively shallow depths within the detection limits of the 'low and slow' airborne survey. Detection limits for superficial ^{241}Am would be 1-2 MBq, with precise detection limits dependent on the beach geochemistry. At both survey heights, isolated patches of dispersed activity smaller than the field of view of the detector would be indistinguishable from point sources. For a ground based survey with a 3x3" NaI(Tl) detector in a backpack configurations, 40-150 kBq ^{137}Cs sources would be detected. For such detectors at ground heights, patches of dispersed activity smaller than the detector field of view would contain total ^{137}Cs activities at or below the point source detection limit.

The work presented here has reported detection limits for single measurements of ~10 s. In practice a pattern of closely spaced survey lines is likely to observe a point source on multiple passes offset by the line spacing. By utilising data from multiple lines it should be possible to both reduce detection limits further and improve the position estimated for any source that has been located. Such analysis is inherently retrospective, but could be conducted in near real-time during the survey either within the data acquisition program, or by a separate program that might be running in parallel on the same computer or a different computer receiving the data by a wired network or telemetry system.

The Nuvia Groundhog system performance has been modelled using Monte Carlo approaches by NUKEM and UKAEA, in connection with the Dounreay monitoring programme. The corresponding Beach Monitoring Model (BMM), and its associated predicted detection probabilities have been briefly described (Elliot *et.al.* 2006, Tyler *et.al.* 2010). While it is not entirely clear how the background sources and their natural variations were simulated in this work, and the extent to which the results can be directly transferred to the Irish Sea beaches, it is nonetheless interesting to compare the predicted and test performances of these models. The BMM for the Groundhog Mark I predicts a detection probability of 51 ± 22% for a 10^5

Bq ^{137}Cs source at 10 cm depth, with detection probabilities determined from sandpit experiments of 42 ± 8% for a uniform background and 75 ± 7% for a variable background. Beach trials for Groundhog Mark I and Evolution produced detection probabilities of 88 ± 3% and 100% respectively under test conditions near Dounreay. Groundhog Evolution detection limits were estimated at 10-100 kBq ^{137}Cs at 10 cm, with some sources <10 kBq recovered from both Caithness and Cumbria with this system. The predicted detection limits for single measurements for the 3"x3" NaI(Tl) backpack system considered here are higher than those for the Groundhog systems, with predicted detection limits for the airborne system significantly higher. Nonetheless both of these systems can be operated in a manner which would readily meet the SEPA specified performance of being able to locate a 100 kBq ^{137}Cs source at 10 cm depth, and they can both reach environmental locations which would not be accessible in practical timescales for the vehicular systems.

The predicted detection limits may also be compared to the activities of particles recovered from the beaches of Cumbria. Figure 5 shows the distribution of the numbers of particles recovered using the Groundhog systems. Approximately 2% of the particles recovered, carrying 30% of the recovered activity, would be above the detection limits for the low and slow survey design if they were located near the surface. At Dounreay, such a survey design would locate approximately 8% of the particles recovered from Sandside beach, carrying 37% of the activity, and the vast majority of the particles recovered from the site foreshore. This survey pattern should be able to locate most relevant particles (>100 kBq) in <5 cm of sand to within a few metres taking data from multiple measurements. Ground based follow-up with a backpack or vehicular system should then allow relatively rapid recovery.

An assessment of health risks associated with the particles on the Cumbrian beaches (Brown & Etherington 2011, Oatway *et.al.* 2011), which included an estimation of the particle distribution based on the recovered particles and habits surveys, concluded that the health risks of the particles are very low. Accidental ingestion of sand was found to be the most significant health risk, with inhalation of suspended particles and external exposure from particles that adhere to skin or clothing also considered. This assessment was based on an assumption that the most active particles in the environment are not significantly more active than the most active particle recovered to date. Specifically, the assumption is made that there are no particles with ^{241}Am activity in excess of 10 MBq, and that particles with beta activity in excess of 300 kBq are only located on the foreshore of the Sellafield site where there is limited public use. This assessment included formal advice to the Environment Agency, with criteria for prompting an urgent review of health risks including “finding an object with a total activity of alpha-emitting radionuclides greater than 10^7 Bq” and “a skin dose rate greater than 300 mGy per hour following characterisation of objects with a caesium-137 activity greater than 10^5 Bq”. Particles of such activities, especially near the surface where members of the public are more likely to encounter them, would be within the detection limits of airborne survey systems.

Particles of a few kBq ^{137}Cs activity would still present contact doses of several mGy h^{-1}, which are not negligible doses although the health assessment (Brown & Etherington 2011, Oatway *et.al.* 2011) considers the committed effective dose from such sources to be small due to the relatively short exposure period from particles temporarily adhering to skin or clothing. Particles with such activities would be below detection limits for airborne systems. Ground based systems are able to locate some particles with lower activity. The health assessment also acknowledges that some particles recovered from the beaches near Sellafield are characterised by high beta dose rates with low gamma activity, most likely to contain ^{90}Sr, similar to the 2003 find. Of 1233 finds up to 31st March 2011, 27 have been classified as "excess beta-rich" (Sellafield 2011). This almost certainly under-represents the abundance of such particles in the environment, as the gamma spectrometric approaches utilised for beach monitoring are much less sensitive to particles with a very low gamma emission rates.

Figure 5 also shows the relationship between particle activity and depth of recovery. The greater number of lower activity particles recovered from shallow depths is due to the greater sensitivity of the monitoring equipment to low activity sources near the surface compared with more deeply buried sources. There is a slight correlation between activity and depth, with all five of the particles with ^{137}Cs activities greater than 500 kBq recovered from below 20 cm. If uniformly distributed with depth, it would be expected that 2-3 particles of this activity would have been recovered at shallower depths. The apparently deeper burial of these more active particles could be a statistical effect due to the relatively small number of such particles recovered. It may also be that there is a physical mechanism relating to the release and subsequent movement of particles. The more active particles could have been released earlier, and so been buried to a greater depth. In addition, the more active particles are larger, with dimensions >2 mm, and wave action may result in them migrating to greater depth than smaller grains. If the greater activity sources are located at greater depth, this would also have an impact on the risks of inhalation or external exposure.

AGS detection limits of low and slow survey should allow a rapid assessment of whether particles >300 kBq ^{137}Cs or >1 MBq ^{241}Am are present on a beach. The survey design for detection limits of 100 kBq ^{137}Cs are also achievable. Both survey designs would be considerably more rapid than ground based approaches. The Groundhog system currently used surveyed 1116 ha of Cumbrian beaches in 693 days (to December 2010), giving an average survey rate of 1.6 ha d^{-1}. The backpack system has a survey rate of ~0.5 ha h^{-1} for each system used. The detailed airborne surveys would cover 5-15 ha h^{-1}, depending on the required detection limit, an order of magnitude greater than Groundhog coverage rates. For beta rich particles of 100 kBq the HPA health assessment (Brown & Etherington 2011) estimated 0.02 particles/ha for beaches at Seascale. Assuming detection efficiencies of 100% for the Groundhog system and 95% for the very low airborne survey designed to reach this detection probability, surveys of beaches would be expected to locate particles with >100 kBq ^{137}Cs activity at a rate of 1 per week for the Groundhog and 1 per 2 h sortie with the aircraft for beaches with 0.02 particles/ha.

In the vicinity of Dounreay, the particles recovered have been on average more active than those recovered near Sellafield, although the numbers of particles are much smaller. The most active particle recovered to date from Sandside beach contained 500 kBq ^{137}Cs, with the most active particle recovered from the foreshore of the Dounreay site containing 200 MBq ^{137}Cs (DSRL 2011). Small numbers of low activity particles have been recovered from beaches more distant from the site. The assessment of health risks associated with these particles has been expressed in terms of consequences of contact with the most active particles (Harrison *et.al.* 2005), and the chances of contact (DPAG 2008). The consequences of contact with the more active particles recovered from the foreshore of the site has resulted in this section of beach being closed to the public. It has been estimated that there is a 1 in 20 million chance of a frequent occupant of the Sandside beach encountering a relevant particle, and a 1 in 60 million chance of a bait digger encountering a significant particle if such a particle were to remain on the beach for more than two weeks. Surveys of the areas used by bait diggers are conducted every two weeks. Assuming similar particle detection limits for the Caithness coastline as estimated here for the Cumbrian beaches, airborne survey techniques would also provide a similar rapid survey of relatively large areas with detection limits that would be useful in locating and removing the higher activity particles that might be present in the environment at Sandside and the Dounreay foreshore, and verification of the absence of relevant particles on other beaches.

Practical work to verify the results demonstrated in this theoretical study have yet to be undertaken. It is noted that the results of this study are consistent with previous survey results, and other work investigating source detection using airborne systems. Searches for lost radiography sources have included an assessment of detection limits with field verification, and have demonstrated the ability of AGS to detect such sources within their transport shields (Sanderson *et.al.* 1988, Sanderson & Allyson 1991). Full energy peak responses for these assessments used analytical models of attenuation in air, which agree very well with the Monte Carlo codes subsequently developed. International exercises including searches for hidden sources have shown that partially shielded ^{137}Cs sources of <500 MBq are readily located using a rapid airborne survey pattern, even in areas with high levels of Chernobyl derived dispersed activity (NKS 1997, 2002), consistent with detection limits below 100 MBq even in challenging environments. At the Resume95 Exercise, the smallest source detected was 26 MBq. Following the break-up of Cosmos-954 over Canada in 1978, airborne techniques were used to locate radioactive particles upto several MBq activity. Previous rapid surveys of the West Cumbrian coastline (Sanderson 2000), and elsewhere, have also demonstrated the detection of small dispersed patches of ~10 MBq ^{137}Cs activity, consistent with the detection limits estimated here for such surveys.

Investigation of detector collimation and spectral processing methods to utilise the scattered energy components of measurements could be of benefit in assisting in distinguishing between patchy dispersed activity and discrete sources, and further reducing detection limits. Data processing that utilises spatial correlations between spectra recorded on adjacent survey lines would increase the effective integration time of measurements near point sources, and thus should reduce detection limits compared to those reported here and the uncertainty for the source location. The use of HPGe detectors could also be explored. Such detectors have a significantly lower efficiency compared to the large volume scintillators simulated here, but also significantly reduced background interferences, and may be particularly useful in detecting ^{241}Am rich particles. Externally mounted HPGe detectors have previously been used when sensitivity to low energy gamma rays is required (Sanderson *et.al.* 1997).

Estimates of the flight parameters required to give a detection limit of 100 kBq for ^{137}Cs particles at 10 cm burial shows the need to fly lower and slower than the 15m 15 knot 'low and slow' surveys explicitly simulated here. There are some practical issues with such surveys, however they are not insurmountable. Low level, high density surveys over public beaches have the potential to cause disruption to people using those beaches. Vehicular surveys of beaches also disrupt the general public. Previous airborne surveys over beaches in Cumbria, including surveys under the 'low and slow' conditions, have not resulted in any complaints from the public. The risks associated with airborne surveys are very small, and low level slow surveys have been safely conducted in sensitive environments such as within the boundaries of nuclear sites (Sanderson *et.al.* 2004). There are also concerns that any active particle on the surface of the beach might be disturbed by the down-draught from the helicopter rotors during a very low level survey. Subject to verification by field trials or further simulation, it is expected that survey heights of 5 m or more would be adequate to collect data with a 100 kBq at 10 cm detection limit. These heights exceed the usual heights used by aircraft while taxiing at airfields which rarely results in disturbance of surface sediments. Likewise, when operating from sites with gravel surfaces our experience is that sediment movement only occurs just prior to take off, and ceases once the helicopter is >1 m off the ground. It has been reported that speeds in excess of 15 ms^{-1} and ground clearances above 15m are required to exclude resuspension risk, although we have not seen the data to support this. Alternative airborne platforms without the potential for disturbance from helicopters might be considered, for example ground towed neutral buoyancy aircraft.

6. Conclusions

A study has been conducted using Monte Carlo simulations of detector response to investigate potential roles for airborne radiometric survey approaches in locating radioactive particles on beaches in Cumbria, to improve the rate of detection and recovery of the most active particles and hence reduce public health risks.

Detection limits in areas with relatively uniform background radiation distributions have been estimated. For rapid, 'low and slow' airborne and 'backpack' surveys, detection limits for superficial ^{137}Cs sources are 5-10 MBq, 200-300 kBq and 30-50 kBq respectively. Detection limits for ^{137}Cs at 10 cm depth a factor of 4 greater. For the 'low and slow' survey design detection limits for ^{241}Am are 1-2 MBq. A survey design with ground clearances of 5-10 m and speeds of 2 m s^{-1} would be required to bring airborne detection limits for ^{137}Cs sources at 10 cm below 100 kBq.

Beaches in Cumbria often contain low levels of dispersed ^{137}Cs activity. Where this activity is found in patches of dimensions smaller than the field of view of airborne detectors, airborne surveys are unable to distinguish between these and point sources of comparable activity using full energy peak information alone.

Airborne methods can demonstrate the absence of sources >5-10 MBq ^{137}Cs within large areas, and identify areas where patchy anthropogenic distributions would require further ground based investigations to confirm the absence of sources. Rates of area coverage and detection for relevant sources significantly in excess of ground based approaches have been demonstrated. Thus, AGS has an important role in identifying where valuable ground-based resources should be focussed.

Equipment deployment and data processing for airborne surveys better suited to the requirements of source detection could be developed. These developments could include detector collimation to reduce field of view to enhance the ability to discriminate between point sources and patches of dispersed activity, greater utilisation of scattered energy components in the spectra, near real-time analysis of spectra from different survey lines, and the routine deployment of externally mounted HPGe detectors to enhance signal to background ratios, particularly for ^{241}Am detection. The simulations here utilised spectral windows processing methods, other analysis methods including deviations from rolling average backgrounds (Cresswell & Sanderson 2009, Kock *et.al*. 2010) or statistical analysis of spectra (Dixon 2004) may also be used in real time, or near real time.

The results of the modelling conducted here have not yet been validated in field trials on the Irish Sea beaches, although they are in general agreement with previous experience from source searches, international exercises and other studies. The results presented here should be applicable to other situations where radioactive particles are an environmental concern, or where tracing radioactive particles may assist in understanding environmental processes. The results should also be of benefit in other scenarios where detection of point sources is required, for example in locating lost or stolen radiotherapy sources. For particles of anthropogenic activity with high yields of medium to high energy gamma rays (eg: ^{137}Cs, ^{60}Co, ^{192}Ir) detection limits can be estimated from this work, accounting for differences in gamma ray yield, for the survey designs presented here. The work can be extended to other survey designs. Detection limits for sources of enhanced natural activity (eg: ^{226}Ra or depleted uranium) will be highly dependent upon local background variations.

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	Description	Major Elemental Concentrations (%)			
		Fe_2O_3	K_2O	MgO	CaO
Skiddaw Group	Ordovician mud and siltstones	10-14[a]	2.0-3.5 [a]	0.9-1.3 [a]	0.3 [a]
Borrowdale Volcanic Group	Ordovician andesitic basalts	10-14 [a]	2.5-3.5 [a]	1.0-3.0 [a]	0.3-2.0 [a]
Windermere Group	Ordovician-Silurian calcareous siltstone and impure limestone	4-10 [a]	2.5-3.5 [a]	2.3 [a]	0.1-0.5 [a]
St Bees	Triassic-Permian sandstone	1-3 [a]	1.5-2.5 [a]	<0.2 [a]	<0.06 [a]
Sellafield		2.4 [b]	3.1 [b]	0.9 [b]	3.7[b]
Solway Sediments		1.8-2.2[c]	1.3-1.7 [c]	0.7-1.3 [c]	1.7-3.1 [c]
Allonby, Whitehaven and St Bees		1.5-1.9[d]			

Table 1: Main rock groups in West Cumbria. Major elemental concentrations are taken from [a]BGS (1992), [b]NIREX geological investigations of Sellafield, [c]Jones et.al. (1999, 2009), and [d]McCubbin *et.al.* (2004).

	Composition				
	1	2	3	4	5
	Mean	Higher Ca, Mg, K, Al	Lower Ca, Mg, K, Al	Higher Fe	Lower Fe
SiO_2 (%)	60	55	65	59	65
CaO (%)	6	7	5	6	5.25
MgO (%)	4	5	3	4	3.25
K_2O (%)	1	2	0.5	0.75	0.75
Al_2O_3 (%)	17	18	16	16	17
Na_2O (%)	4	4.5	3.5	3.75	4
TiO_2 (%)	0.5	1	0.25	0.5	0.25
FeO (%)	5	5	5	8	2

Table 2: Compositions of hypothetical andesitic igneous rocks for evaluation of effects of elemental composition.

	Activity Concentration (Bq kg^{-1}, wet weight)			K %	eU ppm	eTh ppm
	^{40}K	^{214}Bi	^{208}Tl			
High	400	40	6	1.29	3.24	4.12
Medium	300	20	4	0.97	1.62	2.74
Low	200	10	2	0.65	0.81	1.37
		^{137}Cs				
100 % coverage		50				
50 % coverage		25				
25% coverage		12.5				

Table 3: High, medium and low activity concentrations for natural series activity and dispersed ^{137}Cs along the Cumbrian coastline.

	Backpack		Low and Slow			Rapid	
Survey design	1 m s^{-1} speed, 1.2 m height and 1 m line spacing. 13s measurement time		5 m s^{-1} speed, 15 m height and 20 m line spacing. 9 s measurement time			30 m s^{-1} speed, 75 m height and 100 m line spacing. 9 s measurement time	
Area coverage rate			1-2 km^2 h^{-1}. < 5km of coastline during a single low tide			10-20 km^2 h^{-1}. > 50km of coastline during a single low tide	
Background	Superficial ^{137}Cs	Buried ^{137}Cs	Superficial ^{137}Cs	Buried ^{137}Cs	Superficial ^{241}Am	Superficial ^{137}Cs	Buried ^{137}Cs
Low	30 kBq	150 kBq	120 kBq	450 kBq	800 kBq	4 MBq	17 MBq
Medium	40 kBq	170 kBq	140 kBq	600 kBq	1000 kBq	5 MBq	20 MBq
Medium + 12.5 Bq kg^{-1} ^{137}Cs			150 kBq	650 kBq	1100 kBq	5.3 MBq	21 MBq
Medium + 25 Bq kg^{-1} ^{137}Cs			160 kBq	700 kBq	1200 kBq	5.6 MBq	22 MBq
Medium + 50 Bq kg^{-1} ^{137}Cs			170 kBq	750 kBq	1300 kBq	6 MBq	23 MBq
High	45 kBq	200 kBq	170 kBq	750 kBq	1300 kBq	6 MBq	23 MBq

Table 4: Detection limits in different uniform background scenarios

Location	Total ^{137}Cs Activity	
	AGS	Finds
St Bees	32.7 ± 0.1 GBq	101 kBq
Seascale	217.8 ± 0.2 GBq	300 kBq
Drigg	230.2 ± 0.3 GBq	89 kBq

Table 5: ^{137}Cs activity on three beaches determined from the March 2000 airborne survey, and the total activity of particles recovered from these beaches.

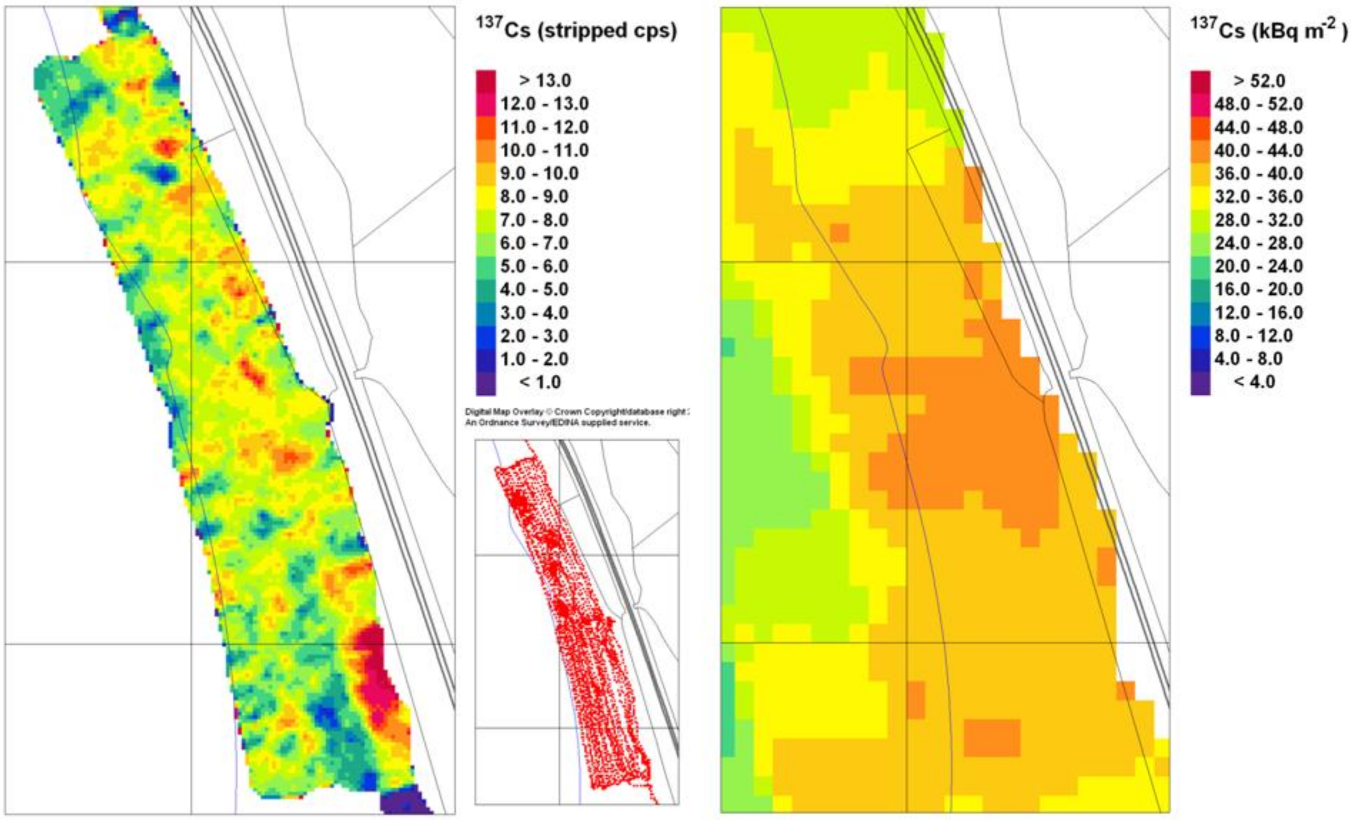

Figure 1: ^{137}Cs distribution determined from airborne measurements in March 2000 (right) and backpack measurements in June 2010 (left).

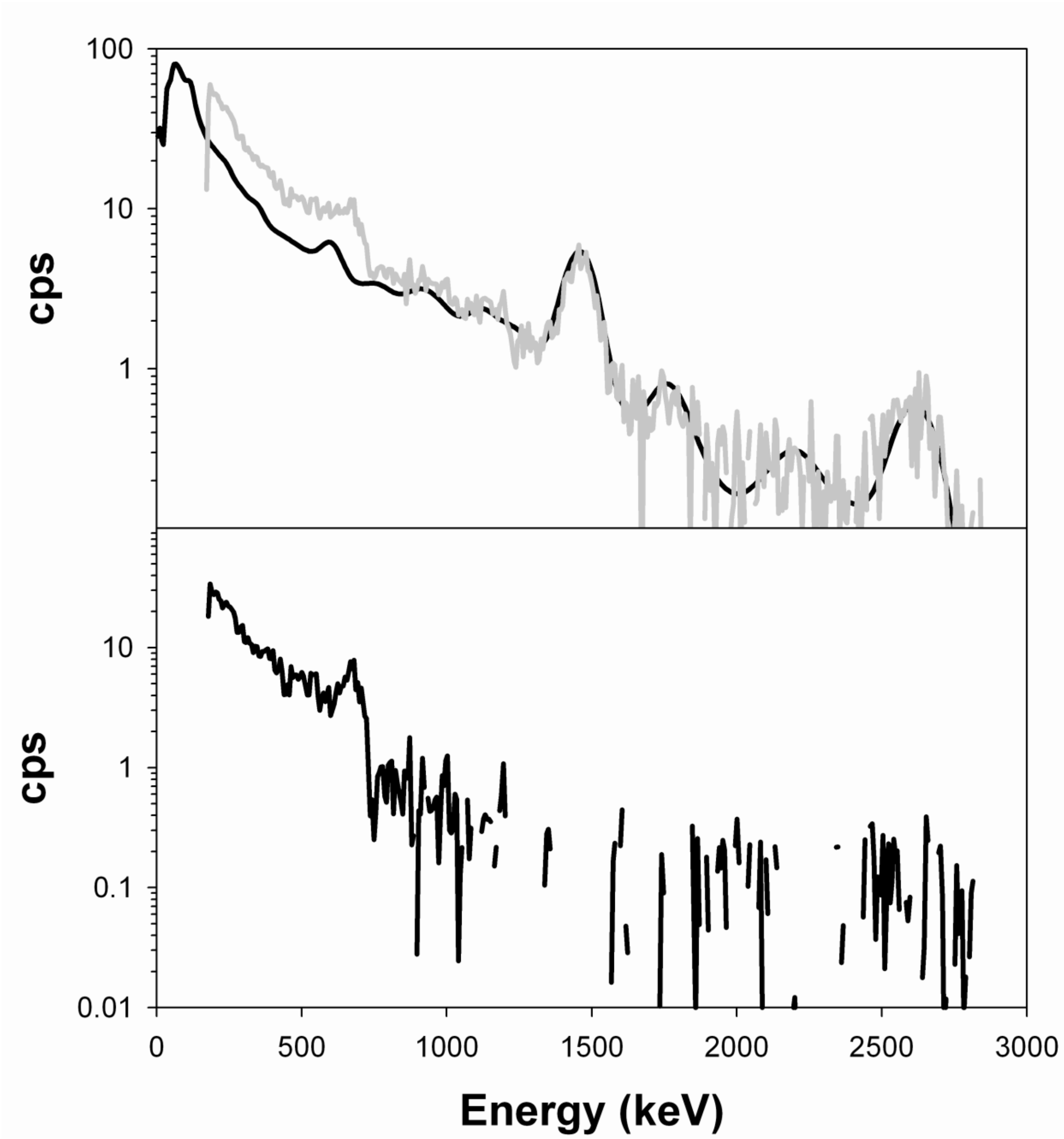

Figure 2. Comparison between simulated (black) and measured (grey) spectra near St Bees, Cumbria, with the residual spectrum (bottom).

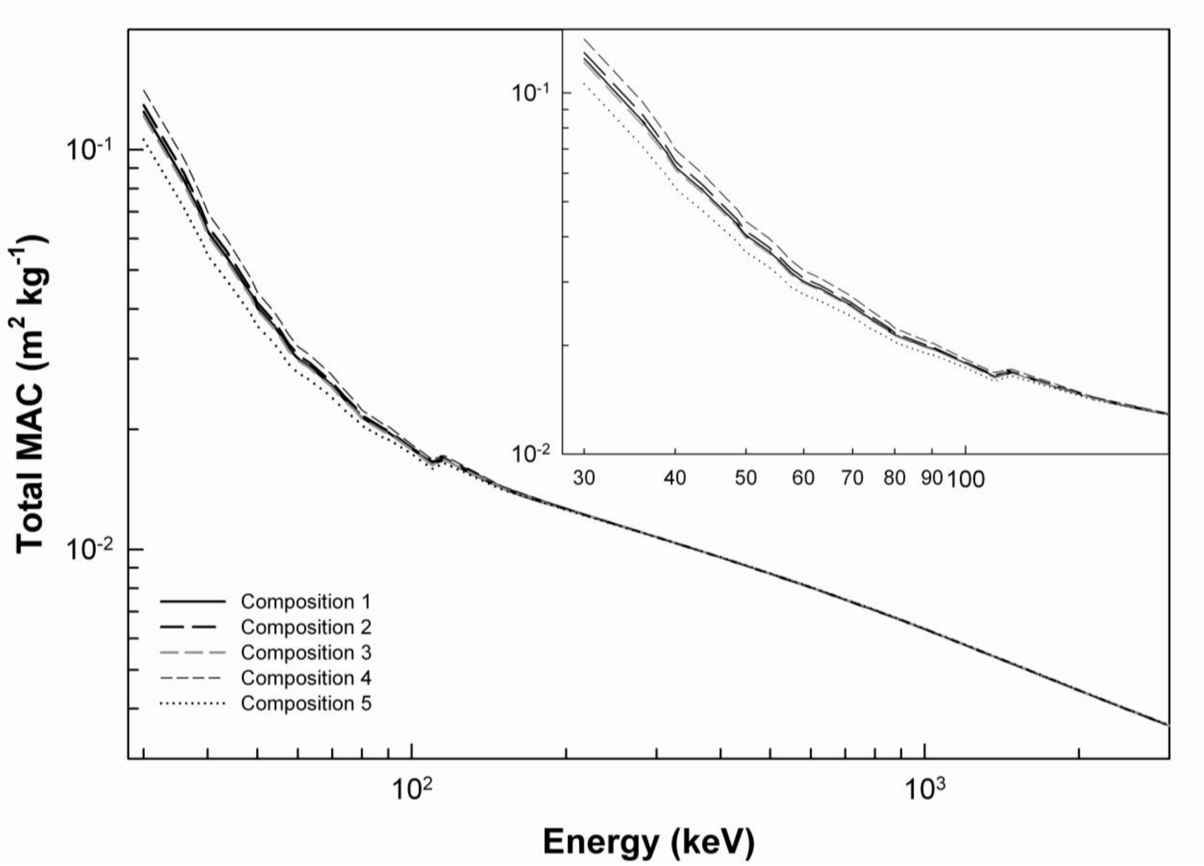

Figure 3: Variation in total mass attenuation coefficient as a function of gamma-ray energy for five hypothetical andesite rock compositions.

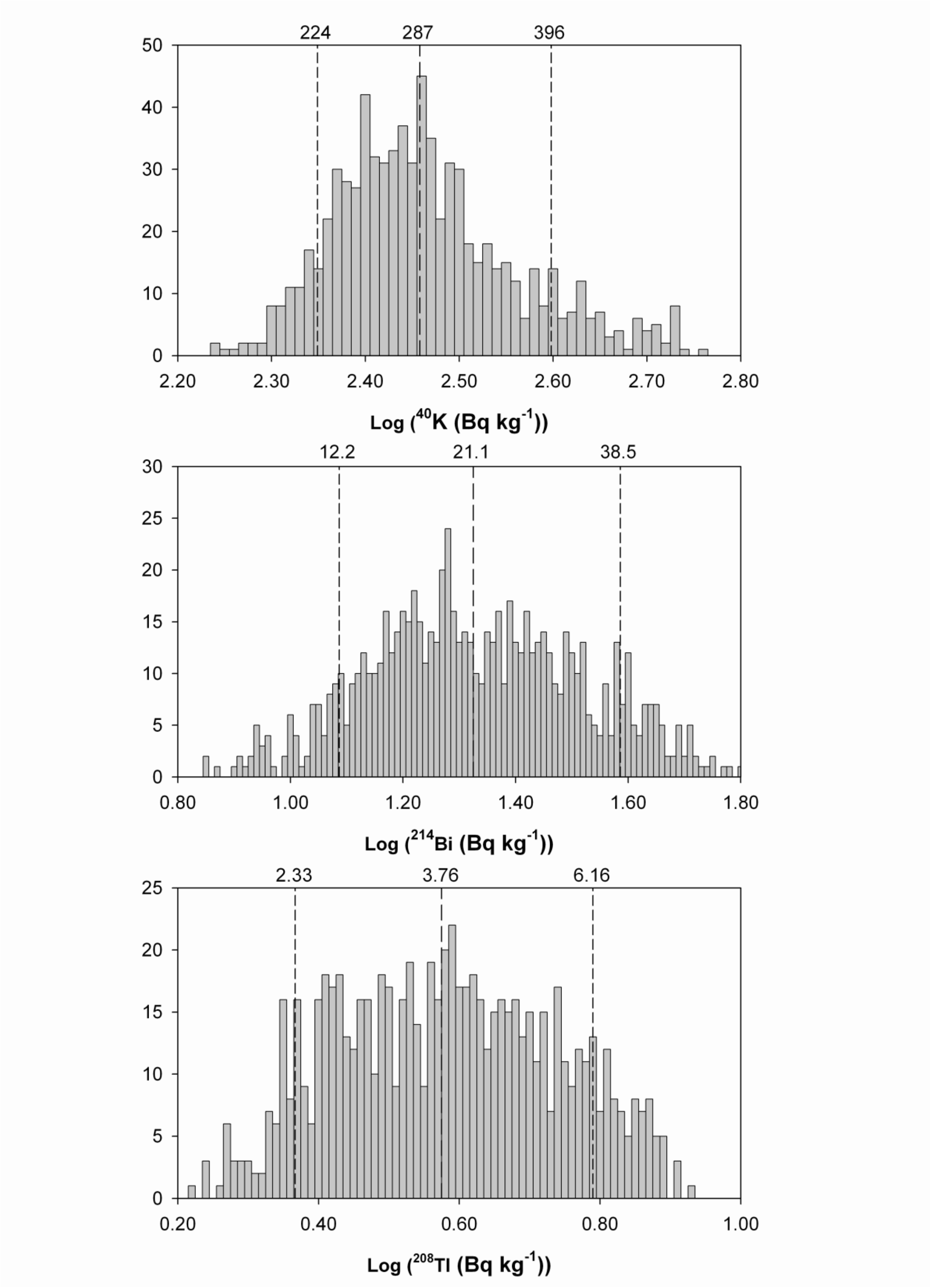

Figure 4: Log-normal histogrammed activity concentrations for natural series activity along the West Cumbrian coast.

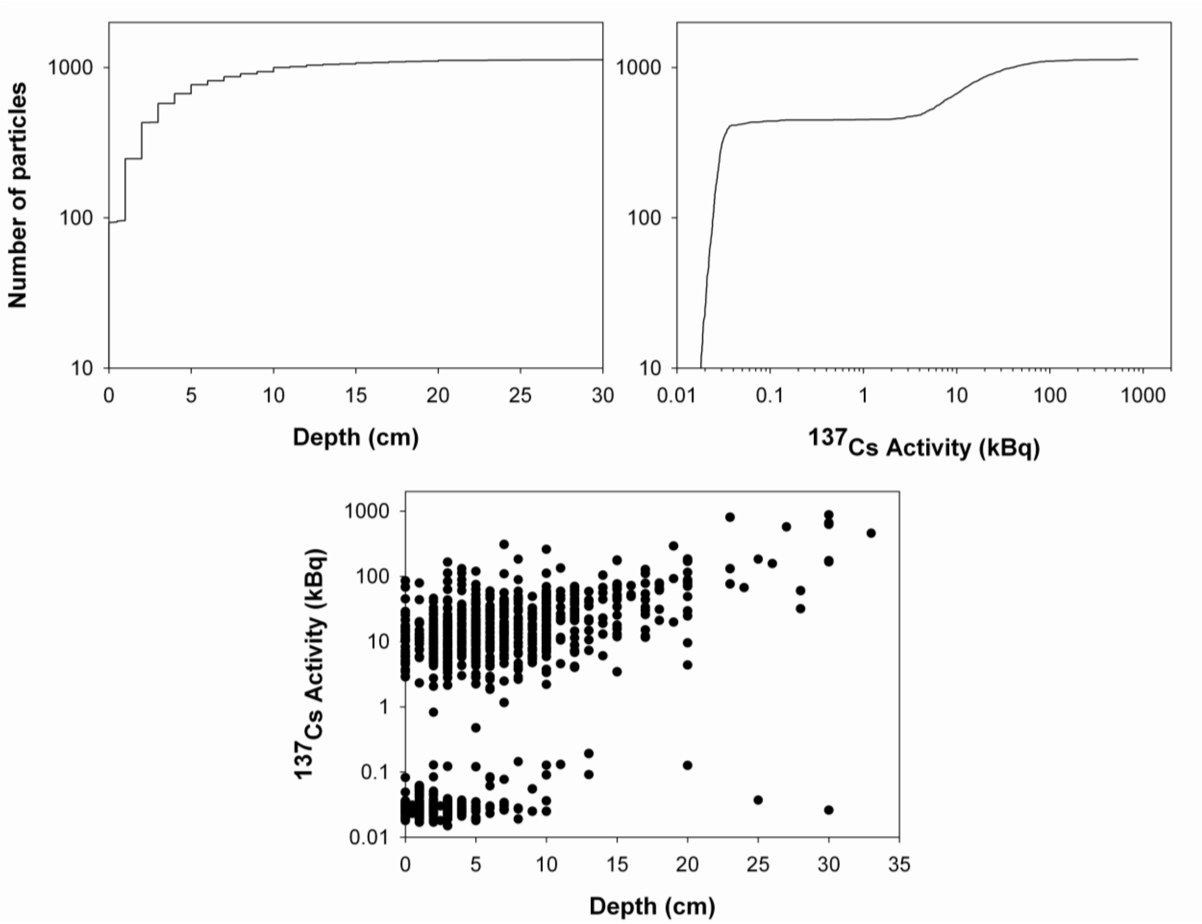

Figure 5: Depth and activity distributions of radioactive particles recovered from Cumbrian beaches. Note that all the particles with <1kBq ^{137}Cs are ^{241}Am or ^{60}Co rich.

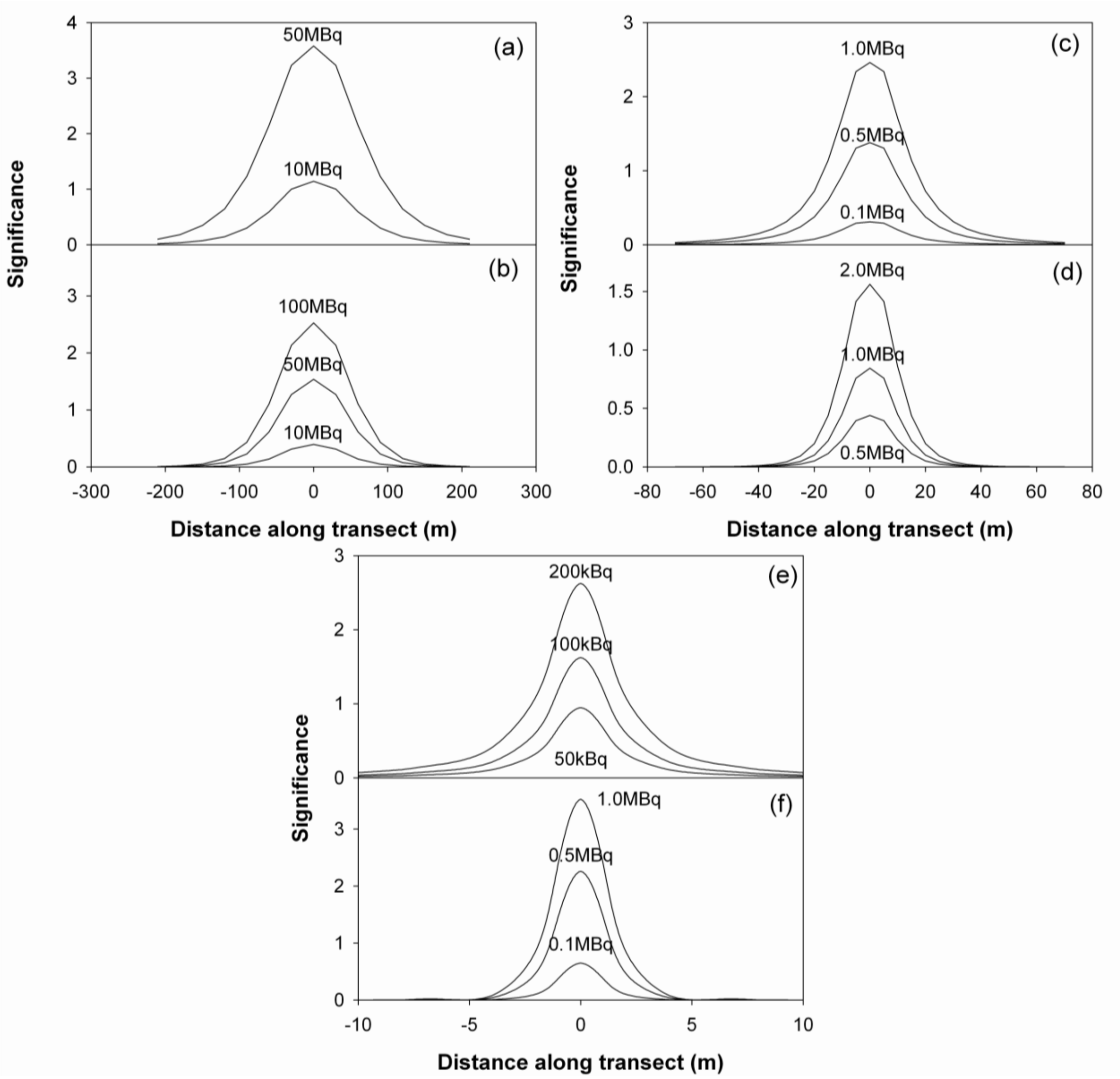

Figure 6: Significance plots for 1s measurements in transects across (a) superficial ^{137}Cs sources at 75m, (b) 10cm buried ^{137}Cs sources at 75m, (c) superficial ^{137}Cs sources at 15m, (d) 10cm buried ^{137}Cs sources at 15m, (e) superficial ^{137}Cs sources with the backpack, and (f) 10cm buried ^{137}Cs sources with the backpack.

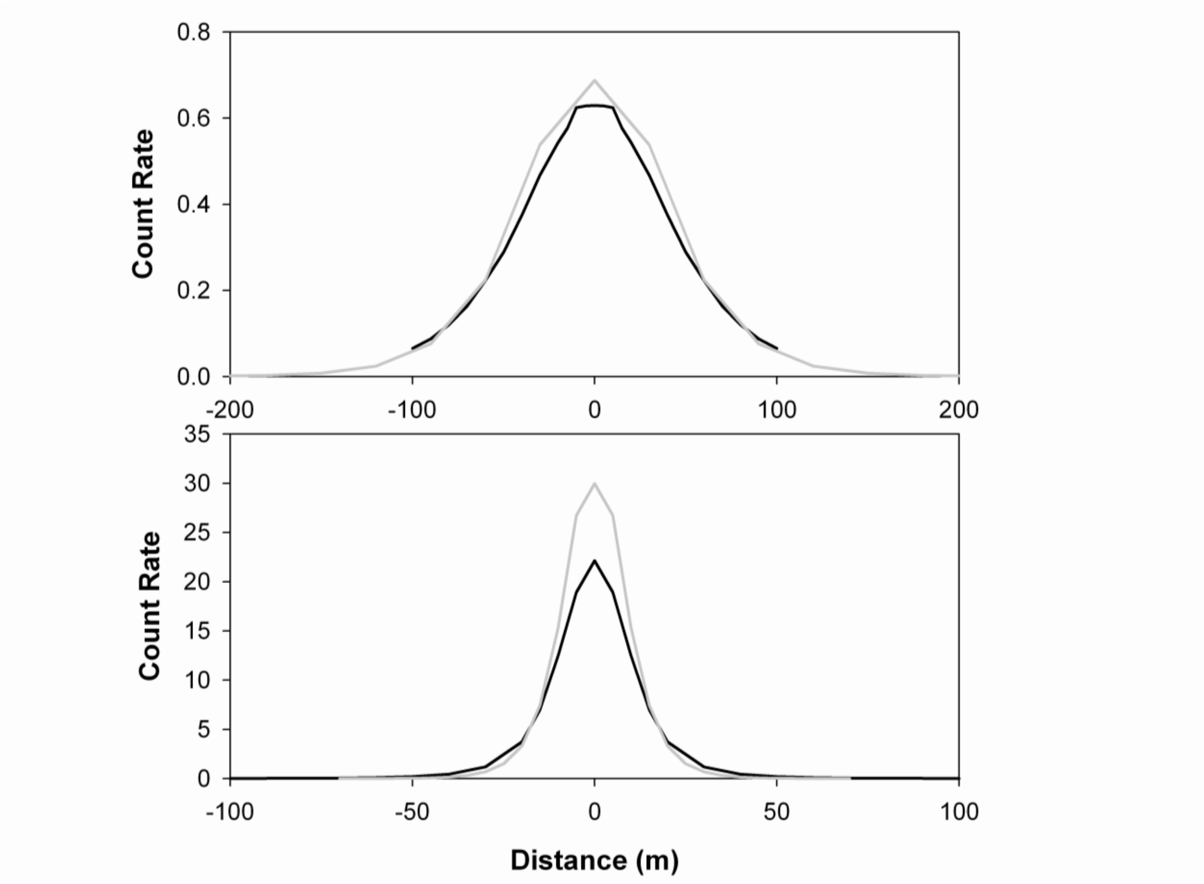

Figure 7: Transects across a 10x10m patch of ^{137}Cs (black) and a superficial 2 MBq source (gray) at 75m (top) and 15m (bottom) ground clearances.

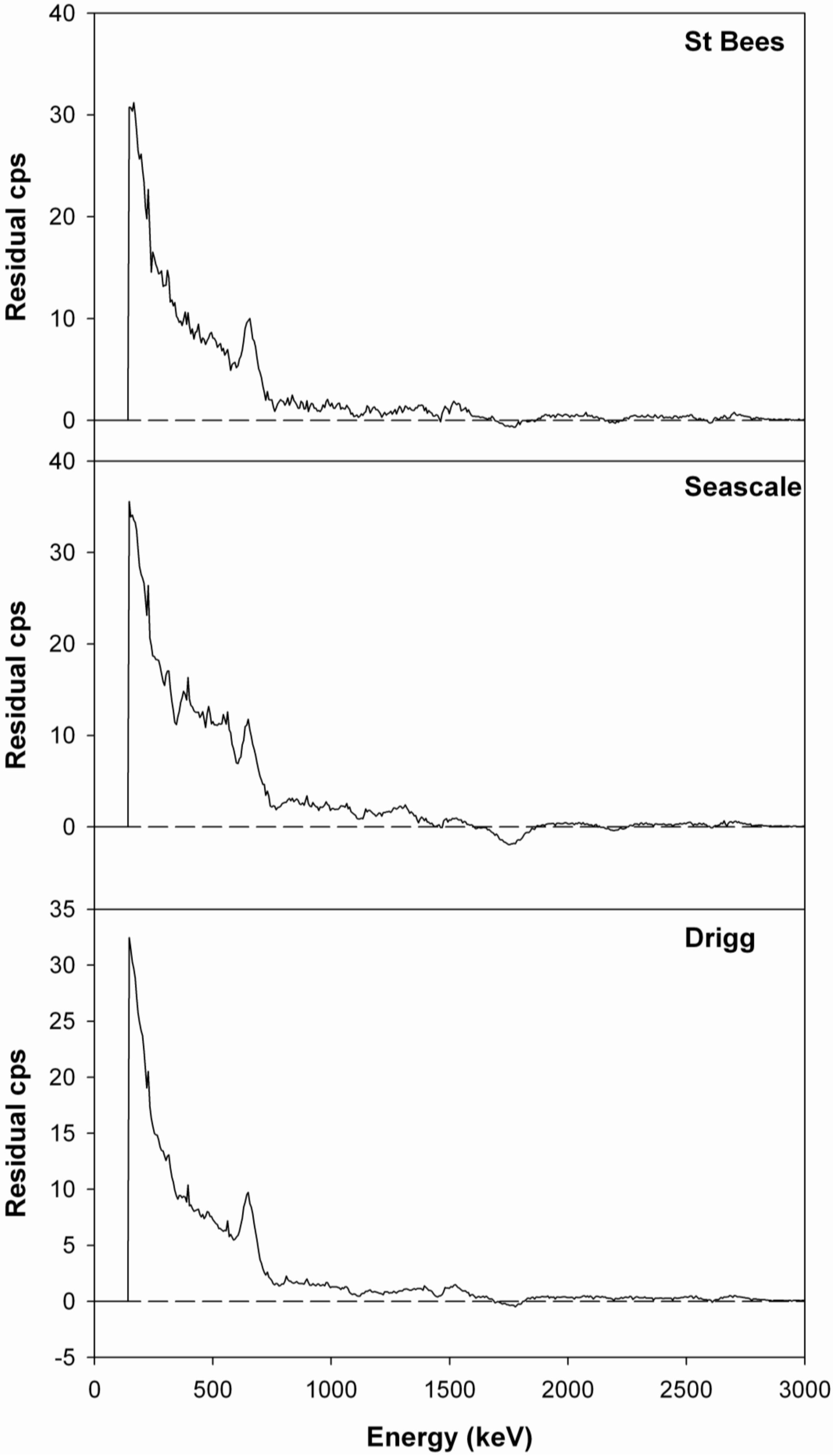

Figure 8: Average residual spectra for three beaches.